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14. ABSTRACT Long-endurance oceanographic sampling platforms such as gliders and profiling floats provide a new opportunity for acquiring acoustic signals from marine animals with immediate applications in conservation and mitigation. Our objective is to produce a reliable system for persistent passive acoustic monitoring of marine animals. The system, comprising both low-power hardware and acoustic processing software, will be extensible and can be incorporated in a variety of autonomous platforms. The design will be open and available for other researchers to adapt and extend.					
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Beta testing of persistent passive acoustic monitors

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LONG-TERM GOALS

Long-endurance oceanographic sampling platforms such as gliders and profiling floats provide a new opportunity for acquiring acoustic signals from marine animals with immediate applications in conservation and mitigation. Our objective is to produce a reliable system for persistent passive acoustic monitoring of marine animals. The system, comprising both low-power hardware and acoustic processing software, will be extensible and can be incorporated in a variety of autonomous platforms. The design will be open and available for other researchers to adapt and extend.

OBJECTIVES

1. Produce 20 DMON digital acoustic monitors for distribution to a group of beta test collaborators. These will be researchers developing systems for acoustic monitoring of marine mammals able to evaluate the device and its software in a range of applications.
2. Support the beta testers with software, hardware and user information.
3. Continue to develop the DMON and its interface with persistent survey platforms. Standardize the user interface to the device using existing open source acoustic monitoring software.

APPROACH

Passive acoustic monitoring (PAM) is used increasingly for detecting the presence and abundance of marine mammals with both scientific and mitigation applications (Mellinger & Barlow 2003; Barlow & Gisiner 2006; Zimmer et al., 2008; Marques et al., 2009). The usual PAM system comprises a mooring which records sound continuously to a hard-drive over several months. The mooring is retrieved periodically at which time the acoustic recording is examined for vocalizations. The 2007-2009 ONR-funded AMT program focused on expanding this technique in two ways. The first goal was to combine acoustic monitoring with mobile oceanographic platforms such as gliders and profiling floats to monitor marine mammal vocalizations and oceanographic conditions over spatial scales of tens to thousands of kilometers (Baumgartner and Fratantoni, 2008). The second focus area was on automatic detection and classification within the PAM device. The capability to process acoustic data on-board autonomous platforms and report detections to ship or shore will greatly increase the efficiency of PAM operations and enable adaptive surveys and real-time monitoring.

Under the AMT program, we developed a small self-contained instrument for real-time detection and classification of marine mammal vocalizations suitable for use on autonomous platforms. The device,

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called the DMON, monitors up to three hydrophone channels and records sound to solid-state memory either continuously or when a detection is made. The on-board processor is capable of running multiple detection and classification algorithms simultaneously. Input channels can be configured for wide-band (blue whale to porpoise) monitoring or for direction finding of signals in a narrower band.

Compared to off-the-shelf computer hardware, the DMON offers several advantages:

1. power consumption is <10% of a PC-based solution. This translates into longer deployments on platforms such as gliders with limited hotel load.
2. the DMON is specifically designed for low noise sound acquisition enhancing its capability to detect weak signals from distant animals.
3. the DMON is much smaller than an off-the-shelf solution making it straightforward to install in a variety of platforms.

Disadvantages of custom devices like the DMON are their complex non-portable software and lack of availability to other researchers. The current project addresses these issues by making a pool of devices available to researchers to install in their own platforms. The devices are supported by a well-documented software infrastructure. Our vision is that the DMON form a reference design for the rapidly expanding field of passive acoustic monitoring.

In the current project, we will build a set of 20 DMONs packaged for stand-alone use and for inclusion in gliders and profiling floats. Five of the DMONs will remain at Woods Hole for continued development of detection / classification algorithms and for field testing. The remaining 15 units will form a loan-out library to allow evaluation of the device within the broader PAM community. We have identified a set of beta test partners who are interested in customizing DMONs for their applications (e.g., by writing software, adapting hardware, and by interfacing the device to other systems) and are prepared to evaluate the device within their existing field studies. We will support these beta-testers with technical assistance, software modifications and documentation. In parallel, we will also continue our work to characterize and extend the performance of the DMON by bench-testing, calibration, and field use within other programs. Two specific focus areas for software design in this, and a companion effort (P.I. D. Fratantoni) are platform interface and real-time detection algorithms.

The DMON has been integrated into two persistent monitoring platforms: the Webb Research Corporation's (WRC) Slocum glider and Apex profiling float. External hydrophones for both platforms provide 10Hz-60kHz monitoring. Serial communications with the vehicle controllers allow feedback of detections via Iridium. A drifting surface float with a cabled array of DMONs has also been developed to facilitate field evaluation of detection and tracking algorithms. The three platforms provide the capability to work over a wide range of spatial and temporal scales. Hardware and software integration of the DMONs in these platforms is being performed primarily within the companion effort. Extension to other platforms and some field testing is included in the current project.

We are developing real-time DMON detection and classification software for baleen whale calls and beaked whale clicks taking advantage of extensive sound data holdings at WHOI. The baleen whale detector involves pitch tracking followed by attribute extraction and classification by quadratic discriminant function analysis. The beaked whale detector incorporates click classification based on spectral and duration cues. In a related project, we are evaluating the detection range of the beaked whale detector using DMON sound recordings of whales tagged with DTAG acoustic recording tags (Johnson & Tyack, 2003).

WORK COMPLETED

Export licensing

As originally planned, the beta-test program included researchers both within and outside of the USA reflecting the international nature of the marine mammal DCL community. We had planned for an open-hardware / open-software design, the goal being a readily-available reference design which would foster performance comparisons and accelerate the acceptance of persistent passive acoustic monitoring. However, upon requesting a commodity jurisdiction back in 2009, the DMON was placed on the US Munitions List and as such is administered under ITAR (International Traffic in Arms Regulations). The result is an export restricted device which considerably limits its attractiveness and ultimately use by foreign collaborators. This required us to somewhat redefine our priorities.

Ultimately, we were able to obtain two licenses in 2010 which allowed us to satisfy most of our prior commitments. The first enabled us to hand carry DMON's into specific countries (notably Canary Islands, Spain) where we were able to deploy DMON's for instrument testing and detection algorithm development. The second was actually a pair of licenses enabling the sale and export of DMON hardware and software to the NATO Undersea Research Center in Italy.

Going forward (late 2010-2011) we had planned the following:

1. Obtain hand-carry licenses for additional countries.
2. Specify a version of the DMON (DMON-Export) which is not export restricted.
3. Identify potential collaborators at foreign universities

Additional hand-carry licenses: Over the past 8 months we have obtained 2 new hand-carry licenses. These cover potential operations in Canada and current operations in Australia. We are currently putting together an application for hand-carries to: France, Greece, Iceland, UK, Norway. The goal is to promote work in those areas.

DMON-Export: In an effort to simplify working with foreign collaborators we determined to obtain commodity jurisdiction (CJ) on the DMON-Export, a non-export restricted version of the DMON. To describe a non-export restricted version of the DMON, we first needed to determine what specifications required modification. For this, we worked very closely with Richard M. Ead (Sensors and Sonar Systems Department, Naval Undersea Warfare Center, NUWC Code 1535), Ted Ioannides (PS 4013) and Dave Sebastian.

Paramount to defining the DMON-Export specifications was a calibration of the device at NUWC, Newport. Again working very closely with Mr. Ead, we prepared two DMON's and modified them to work with NUWC's calibration facilities. We performed tests in two facilities: System K of the Low Frequency Facility (LOFAC) and the Acoustic Pressure Tank Facility (APTF). These tests were done over the course of a single day (with a separate day of test design and setup) and covered a frequency range of 1 Hz to 40 kHz. All frequencies were tested at the following pressures: ambient, 100 psi, 220 psi and 350 psi. The results would largely shape the acoustics parameters of the DMON-Export. (please see figures 4,5 and 6)

For the new CJ application the following changes were advised:

- Built-in 2-pole high pass filter at 500 Hz on all audio channels
- No external timing-synchronization capability

- No user programming capability
- Modified depth rating (800 m)

These changes were incorporated into a modified set of DMON specifications. These specifications were then the basis of a new CJ. In August 2011 we received a favorable decision on DDTC Case CJ 681-11. The determination was that the DMON-Export is not subject to the licensing jurisdiction of the Department of State. The Department of Commerce advises the item be given an Export Control Classification Number of 6A991.

Moving forward with DMON-Export: Given the above specifications, the next steps are to determine how best to implement them and to promote the availability of the DMON-Export. Both user programmability and synchronization can be taken care of with careful software/programming modifications. We plan to utilize programmers here at WHOI to implement a tamper-proof solution but have not yet begun this work. The 800m depth rating will be accomplished by redesigning the hydrophone for a crush rating of 800 meters. As all of the current hydrophones are end-capped tubes this will simply be a redesign of the end-caps. New thicknesses have been calculated but need to be fabricated and tested. Testing is a bit difficult in that hydrophones need to be taken to destruction and ceramics are expensive. We are currently looking into a reasonable (less expensive) means for these tests. It has yet to be determined the best (safest) way to implement the high-pass filter; either analog or digital. We will look into what is the most cost effective way to maintain stock on both DMON and DMON-Export devices. An analog filter is simple but poses stock issues – different hardware for DMON and DMON-Export. A digital filter can be implemented and made tamper proof, in the same way as the non-programmable and synchronization components.

We will be presenting a talk at the 19th Biennial Conference on the Biology of Marine Mammals in Tampa this November. (Abstract title: “DMON as the Basis of a Low Power, Low Noise Passive Acoustic Detection and Monitoring System”) This will be the first opportunity to present the non-restricted version of the DMON to the community and we are anxious to learn if there will be interest.

Beta-Test Program

The original plan was to build 20 DMONs to be dispersed amongst a select group of collaborators, providing support as necessary. We currently have 19 bottles and 8 card sets built and functional. Of these, 13 bottles and 6 card sets are out with customers. (please see table 1) Each client has received 1-3 DMONs in one of two form factors: (i) a board set ready for installation in a vehicle (Fig. 1), or (ii) a stand-alone instrument ready to be deployed at sea (Fig. 2). Each DMON has three independent sound acquisition channels and clients elected whether these were configured for LF (10-8kHz), MF (100-60kHz) or HF (1k-150kHz) operation. The stand-alone instrument contains 3 hydrophones and is capable of operation at up to 2000 meters depth. The board-set option is intended for bench test evaluation, code development and integration into gliders, AUVs or profiling floats. A simple but robust host interface serves as a platform-independent means to upload data and download programs to DMONs.

While operations vary, current work has ranged from deploying DMON bottles on existing moorings to vehicle integrations. Notable deployments this year included:

- | | | |
|------------------------------|-----------------|----------------------------|
| • Andy Read | Cape Hatteras | Beaked whales and dolphins |
| • Dani Cholewiak/David Wiley | Stellwagen Bank | Humpback Whales |

• Gerald D'Spain	SCORE range	ZRay glider applications
• Brian Bingham	Hawaii	wave glider applications
• Manuel Castellote	Alaska, Cook Inlet	beluga monitoring
• Aguilar De Soto / Johnson	Canary Islands	pilot and beaked whales
• Tyack / Allen	Australia	Large whales, surf zone noise
• Doug Nowacek	Cape Hatteras	iRobot seaglider operations

Gerald D'Spain deployed a DMON bottle on the fixed wing ZRay glider during the SCORE range validation testing this past January. (please see figure 7) Also present during these tests, David Fratantoni deployed two custom outfitted Apex Profilers and one Slocum Glider running beaked whale detector code. Brian Bingham was provided a card set and a pair of hydrophones which were integrated onto a wave-glider and deployed in Hawaii. Doug Nowacek work involved integrating a DMON onto the iRobot seaglider. All other applications were DMON bottles attached in some way to existing moorings.

DMON development

Duke/iRobot: We worked closely with Duke University and iRobot Corporation to integrate a DMON onto a seaglider. This included a trip to Durham to meet with the iRobot engineering team and finalize both the hardware and software interfaces. This work was similar to the previous years' work integrating a DMON onto the Teledyne/Webb gliders and profilers. (AMT program) The DMON provided acoustic data and communicated some predetermined information (some subset of the data, ie: detections) to the seaglider. The seaglider then passed that data to the shore via iridium link. This system was deployed successfully in Cape Hatteras over this past summer. iRobot also presented this system at the recent AUVSI Unmanned System show in Washington this past August. (please see figure 8)

Programming: The Ann Allen / Peter Tyack work in Australia required custom low sampling code be written to lengthen deployment times. Mark Baumgartner stepped in and wrote code to sample a single channel at 16 kHz thus enabling roughly two weeks of continuous data storage. DMON's with this code were deployed between August and September and we are still awaiting results. This work starts to address one of the main issues we've been looking into: longer duration deployments. While the DMON is ideally suited for integration onto gliders, profilers and moorings many of those platforms are geared toward longer duration experiments. With the low sampling code and internal battery the DMON can accommodate 2 weeks of operation, so to move forward to month or longer deployments we need to address not only storage capacity but also battery capacity.

Future work / development: Attending the recent DCLDE workshop in Oregon, it was evident that the DMON program would benefit from longer duration deployments. While ultimately systems capable of transmitting real-time detections (possibly storing extracts) are the goal, continuous recordings with post-processing capability remains the norm. We had some discussions at the DCLDE workshop with colleagues who showed interest in a DMON with enhanced storage and have decided to look into the feasibility of adding this as an option. This work would not be intended for the current program but as a future growth path for the DMON.

To accommodate long deployments, from a power supply perspective, an external battery input was implemented in the DMON. This input is suitable for sub-month long deployments but needs to be redesigned for anything longer. Our current setup is at best 70% efficient, a number that is largely the

result of charging the internal battery in addition to powering the DMON. Nevertheless, it needs to be increased to be more energy efficient and minimize battery pack sizes. We are currently looking at re-designing the external battery input with the goal of getting the efficiencies up into the 80-90% region.

A questionnaire was circulated and while the results vary in many cases one thing was common amongst our collaborators; we need to provide better documentation (user manual) for the device. This is something we are currently working on, and will continue until we have a proper instrument operation and user manual.

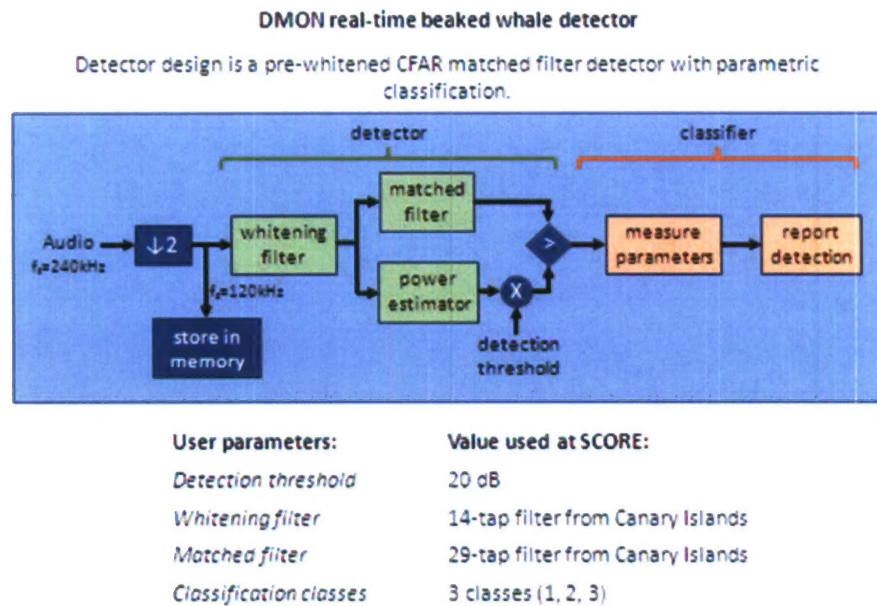
RESULTS

DMONs have again been used in a number of field experiments over the past year, however tangible results are sparse as many customers are either evaluating vehicles as monitoring platforms, have yet to audit sound data or are still getting familiar with the device. We've continued to work with customers to evaluate field performance in an effort to further eliminate failure modes, hardware limitations and software bugs. Beta-test colleagues continue to be primarily positive in their assessments. Complaints have been getting started and documentation, but as stated earlier we are working on alleviating this with better documentation.

With the goal being a move toward persistent monitoring with active, real-time detection, the most tangible results for the DMON thus far are from the SCORE range validation testing this past January. As indicated earlier, 2 APEX profilers and 1 Slocum glider were operated and deployed by David Fratantoni, WHOI. These vehicles were the result of a collaboration between WHOI and Teledyne Webb Research, as stated earlier this work was supported by the AMT program. They represent a custom acoustics integration where the DMON electronics hardware was mounted inside the vehicle dry space and wired to its controller. (see figure 9) Code was developed to enable two-way communication between the two devices. In addition, a custom hydrophone array was designed and built for each platform. The beaked detector code, running on all 3 vehicles, was largely the result of field testing in the Canary Islands in 2008-2010.

The Canary Islands involved DMON deployments as part of a NOPP beaked whale habitat and acoustic detection study (see report by Johnson et al.). DMONs were deployed with software for continuous LF and MF sound recording with loss-less compression, timing acquisition from GPS, and real-time beaked whale detection, all operating simultaneously. DMONs were mounted on cables suspended from drifting buoys placed about 1.5 km apart in 1000m water depth. Each buoy supported a DMON at 20m and 200m depth to mimic the normal deployment depths of towed arrays and sonobuoys. Continuous visual coverage of the deployment area was maintained from a shore station equipped with high power binoculars to compare visual and acoustic detections. The DMON click detector reports the quality of each detection in three categories (Class 1-3) along with additional parameters such as processing gain, SNR and transient duration to help classify transients. Some 550,000 clicks, classified as having a high probability of being produced by a beaked whale (i.e., Class 1) were detected by the 4 DMONs during the experiment. The waveforms of a random subset of 15000 detections were checked to establish the miss-classification rate and to determine what types of non-beaked whale signals tended to confound the detector (Fig. 3). This has led to the adoption of improved classification thresholds in the detector. The large click data-set is being used in a companion NOPP project to evaluate detection rate as a function of range and depth.

The Canary Islands data was used to perfect the beaked whale detector code, the SCORE range testing was the first full-up field test of a DMON on a vehicle running real-time detections. (see below for block diagram of system)



While more work needs to go into the SCORE data (primarily a more exhaustive analysis and comparison against other designs) the DMON real-time detector and classifier provides a robust first cut of possible beaked whale detections and is efficient at rejecting interfering transient sources.

Following are the summary results:

- Whitening filter optimized for ambient noise in Canary Islands; very little improvement when optimizing for SCORE
- SCORE beaked whale clicks were varied in spectrum (different species, size class, genders?) improved matched filter or filter bank may improve performance
- Glider and Profiler motors and pumps are noisy, however duty cycle of noise is low. Therefore they are viable platforms for persistent detection.
- Profilers were particularly effective, glider less effective due to shallow, short dives.

IMPACT/APPLICATIONS

National Security

Concern about potential impacts on acoustically-sensitive cetaceans has constrained some Navy training exercises and has led to lengthy court proceedings. The development of reliable methods to predict and verify the presence of cetaceans will provide the Navy with new tools to help balance preparedness with environmental stewardship.

Economic Development

Economic development brings increasing noise to the ocean from ship traffic and oil exploration. An improved understanding of the abundance and habitat of marine mammals and their use of sound will help to make economic growth sustainable.

Quality of Life

The techniques developed here will lead to improved information about the location and abundance of marine mammals. These results will facilitate improved regional management with implications on ecosystem health.

Science Education and Communication

To the extent possible within export restrictions, we have adopted an open-source approach whereby all aspects of the technology will be available to other researchers. Our goal in doing this is to foster community development of the device and to facilitate the availability of extensible systems for marine mammal acoustics research and training.

TRANSITIONS

DMON devices and technology have been transferred to researchers at NOAA, Scripps Institute of Oceanography and several universities. A subset of the technology has been exported to the NATO Undersea Research Center.

RELATED PROJECTS

D-MONs are being evaluated in several related programs including an NOPP project (P.I. M. Johnson) and the AMT program that was the predecessor of the project reported here (P.I. D. Fratantoni). Other no-cost opportunities to field DMONs are being taken wherever possible to increase information about the performance and limitations of this device.

Funding from SERDP (CS-1188) in 2010 supported the development of a new generation marine mammal tag (DTAG V3). This device shares many software and hardware features with the DMON and there is considerable synergy between these projects.

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Table 1: DMON Beta-Test group

(grey boxes indicate groups that are scheduled to participate but do not yet have a legal agreement).

Contact	Affiliation	Application
d'Spain	SIO	ZRAY glider integration
Thode	SIO	moorings, code development
Mellinger / Klinck	Oregon State University	moorings, autonomous boat gliders and code development
Siderius	Pennsylvania State University	working with OSU
Madsen*	Aarhus University	drifting arrays
Zimmer*	NATO Undersea Research Center	towed / drifting array
Parks	Pennsylvania State University	moorings
Wiley	Stellwagen Banks National Marine Sanctuary	drifting arrays / moorings
Fratantoni / Baumgartner	WHOI	gliders / profilers
Nowacek	Duke University	Seaglider
Hudson	iRobot	Seaglider (with Duke)
Read	Duke University	fishing gear / moorings
Oleson	NOAA	fishing gear
Au	University of Hawaii	moorings / drifting arrays
Wiggins / Hildebrand	SIO	moorings
Matsumoto	NOAA	moorings, bottom seismometry
Howie / Bingham	University of Hawaii	Liquid Robotics Wave glider
Frankel	Marine Acoustics, Inc / U of Hawaii	
Johnston	Duke University	
Castellote	NOAA/Alaska Fisheries	Beluga whale detection and monitoring

* = specially licensed work with non-US person.

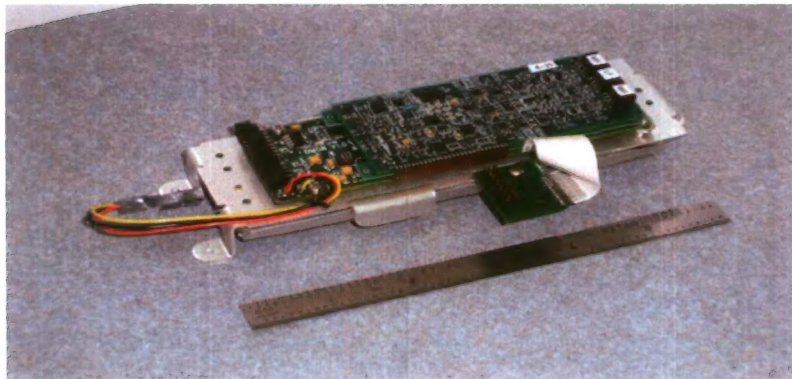


Fig. 1: DMON board set in glider-ready format

The DMON is a set of two circuit boards capable of wide bandwidth acoustic recording and real-time detection. The device consumes little power making it ideal for low hotel load autonomous vehicles like gliders. The format shown here was provided to beta-test clients working on gliders and AUVs.



Fig. 2: DMON in stand-alone configuration

The DMON circuit is pressure tolerant and can be packaged in a low-cost oil-filled housing to minimize acoustic reflections and payload weight. This package was provided to beta-test clients interested in mooring applications or in installing the DMON in the wet-space of a vehicle.

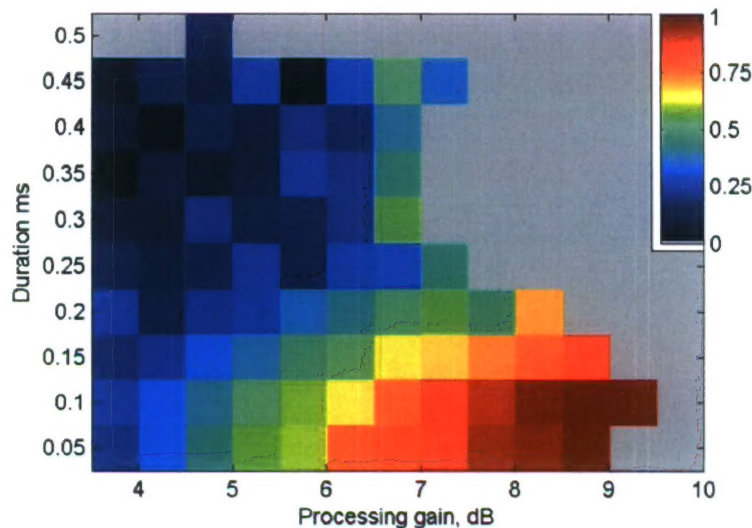


Fig. 3: Field verification of the DMON beaked whale detector in the Canary Islands.

Shown is the proportion of detections considered in post-evaluation to represent an actual beaked whale click, as a function of two click parameters, energy duration and processing gain. Grey regions indicate parameter combinations for which no clicks were received. This plot helps determine how to set parameter thresholds for beaked whale classification. For example, choosing a processing gain threshold of $4 + 10 \times \text{duration}$ (in ms) eliminates many false detections.

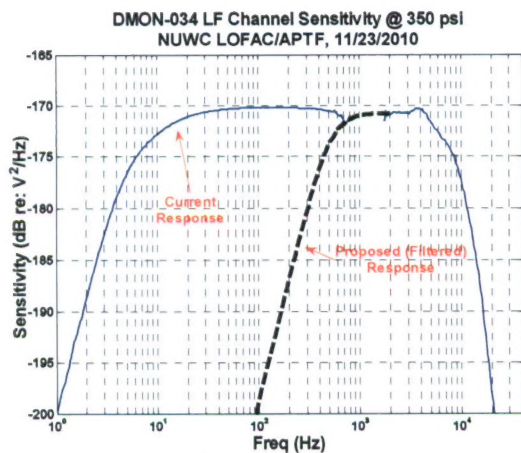


Figure 4: DMON Sensitivity

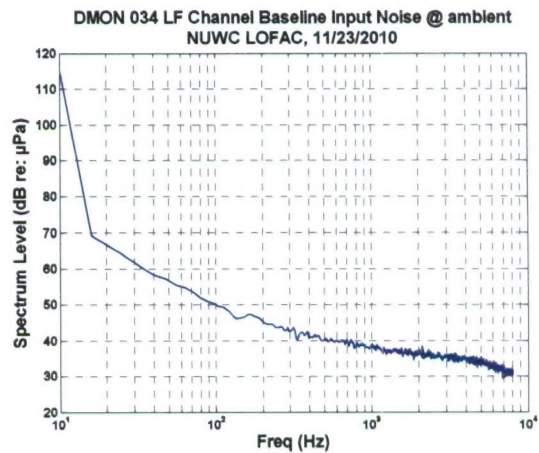


Figure 5: DMON Noise

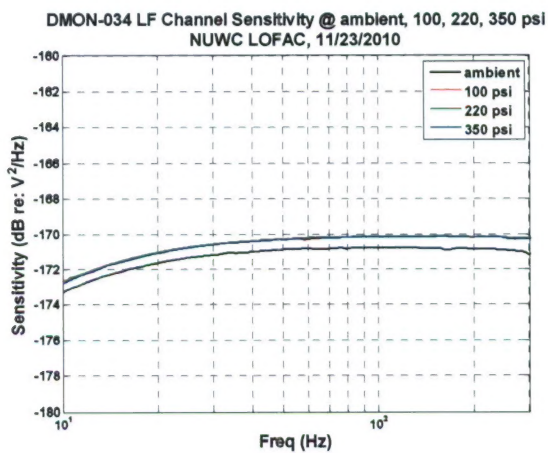


Figure 6: DMON Sensitivity at Depth

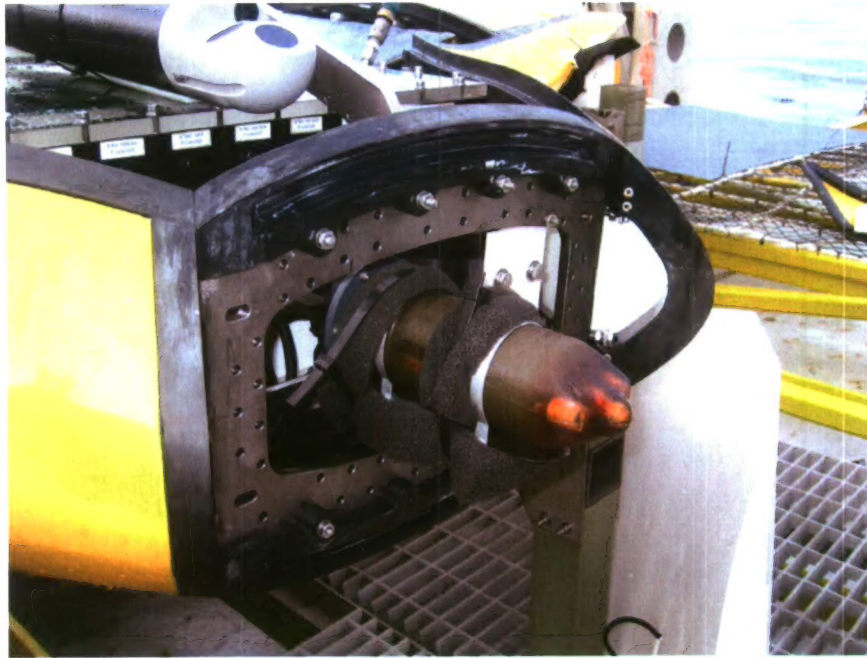


Figure 7: DMON on ZRay Glider
(ready for SCORE deployment)

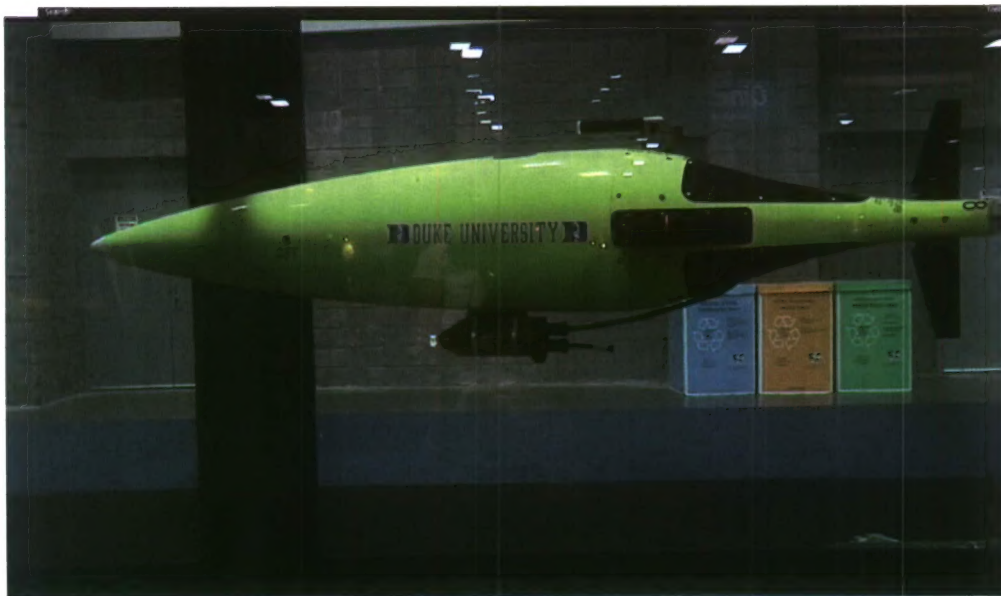


Figure 8: DMON on an iRobot Seaglider
(Shown in tank at AUVSI show in Washington DC)

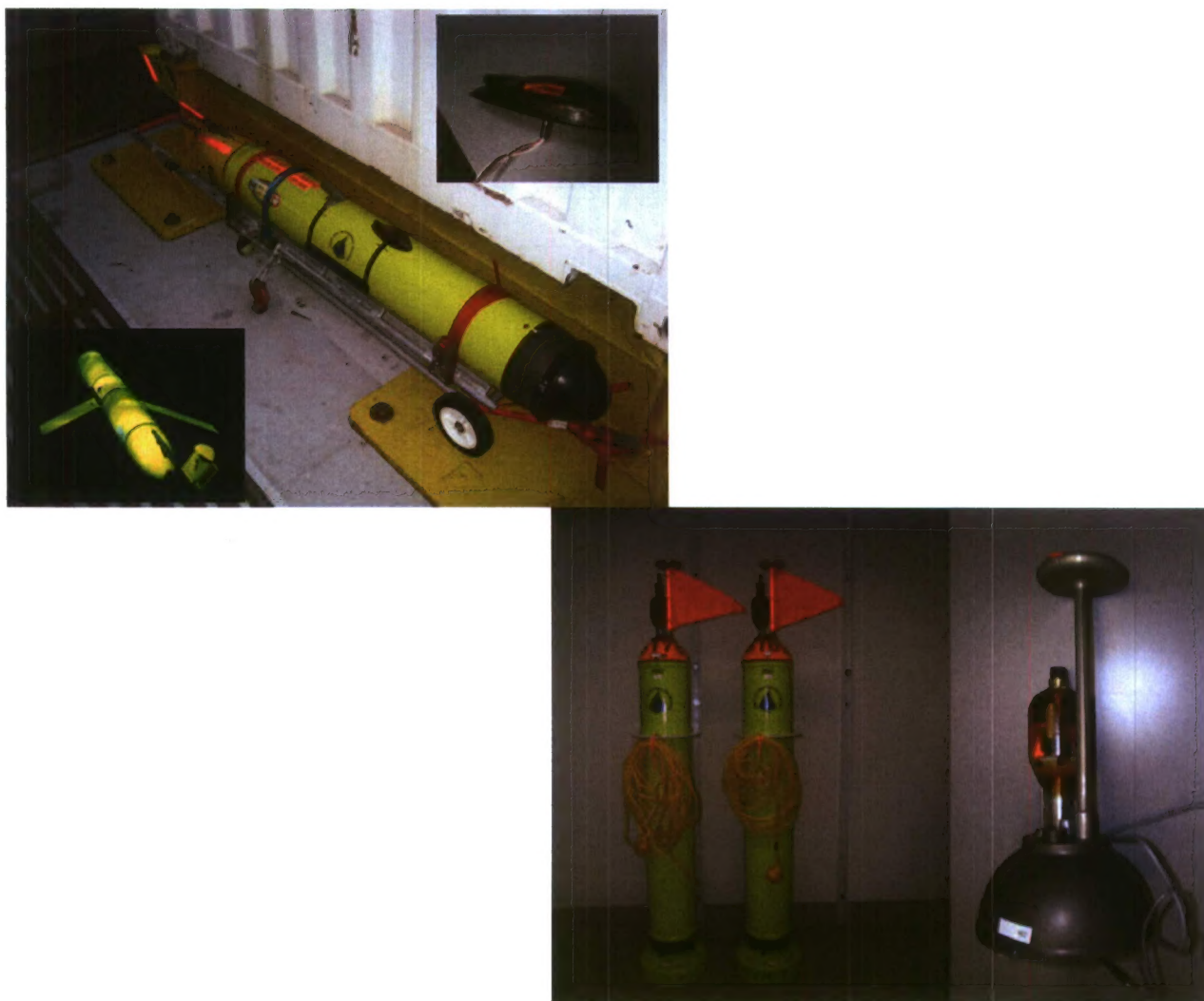


Figure 9: DMON custom integration onto Teledyne Webb glider and profiler